Droplet-based LPP Light Source for HVM Inspection Applications

Nadia Gambino

B. Rollinger, A. Giovannini, L. Bozinova, F. Alickaj, K. Hertig and R. S. Abhari

Swiss Federal Institute of Technology Zurich, Sonneggstrasse 3, CH-8092 Zurich, Switzerland.

F. Abreau

Adlyte Ltd., Industriestrasse 7, CH-6300 Zug, Switzerland.

Outline

- Introductions

  LPP Light Sources

- ALPS Facilities

  ALPS II, ALPS I, Droplet Test Facility

- ALPS II EUV Light Source

  Main source performance and recent source optimizations

- ALPS I Facility

  Laser Plasma Physics and comparisons with numerical simulations

  Studies on alternative fuels

- Summary

LPP Light Sources

- Laser Produced Plasmas are promising as Soft X ray light sources

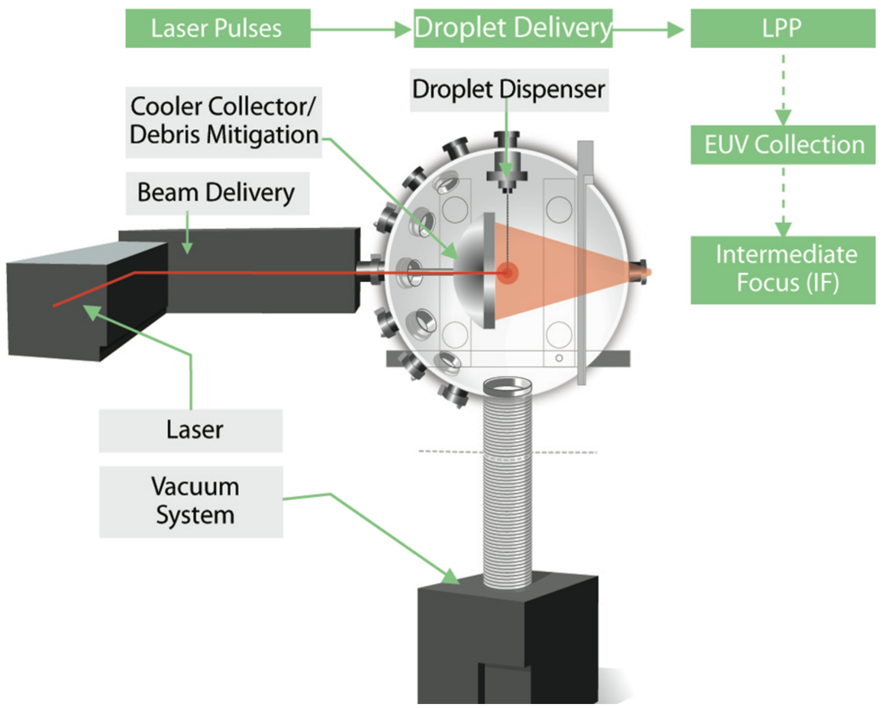
- ➢ Most promising light source for EUVL at 13.5 nm (HVM SoCoMo)
- ➢ Light source for inspection applications (actinic inspection, other inspections)

- EUV sources challenges for actinic inspection applications

- ➢ Brightness
- ➢ EUV Stability
- ➢ Life time of the source

Key technology for the source:

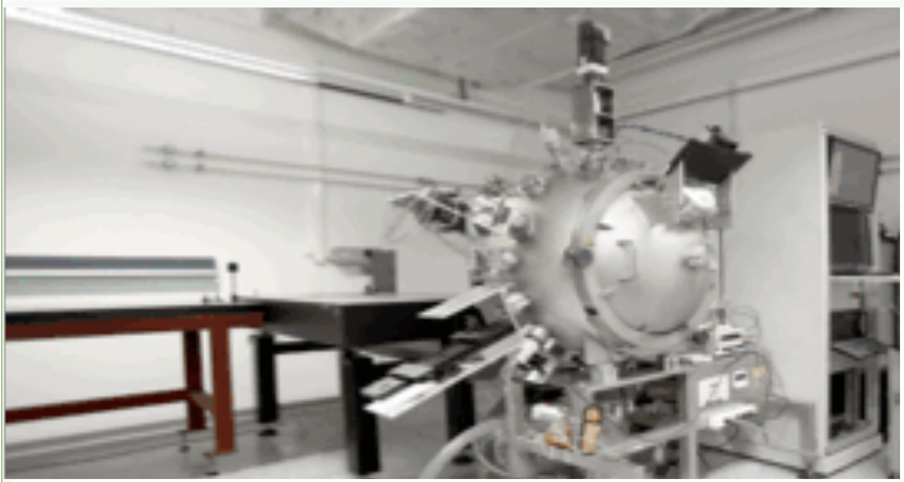
Laser Produced Plasmas with the use of **tin droplet targets**
EUV @ 13.5 nm in 2% bandwidth
(Sn^{8+} to Sn^{12+} ions)



ALPS Facilities at ETH Zurich

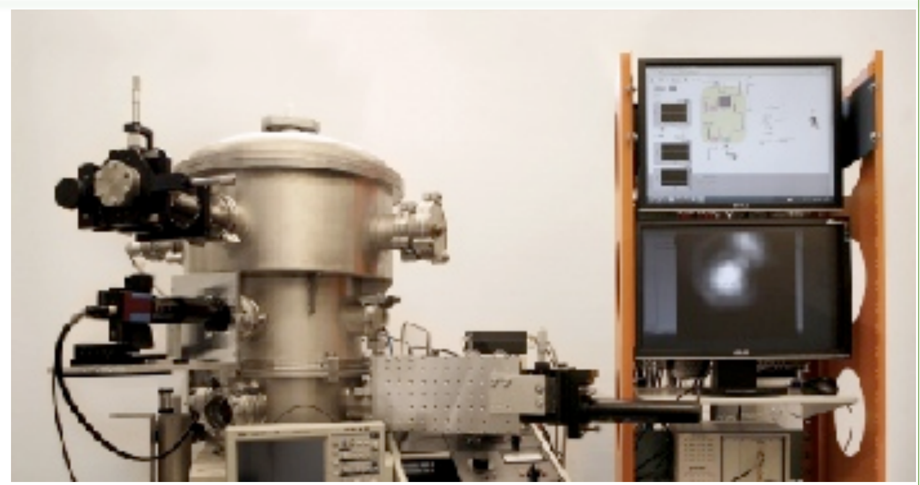
ALPS II (2013)

- High brightness inspection tool for HVM
- Engineering test stand for long-term operation and lifetime studies (> 8 hours).



ALPS I (2007)

Plasma physics studies & diagnostics development



DTF-Droplet Test Facility (2009)

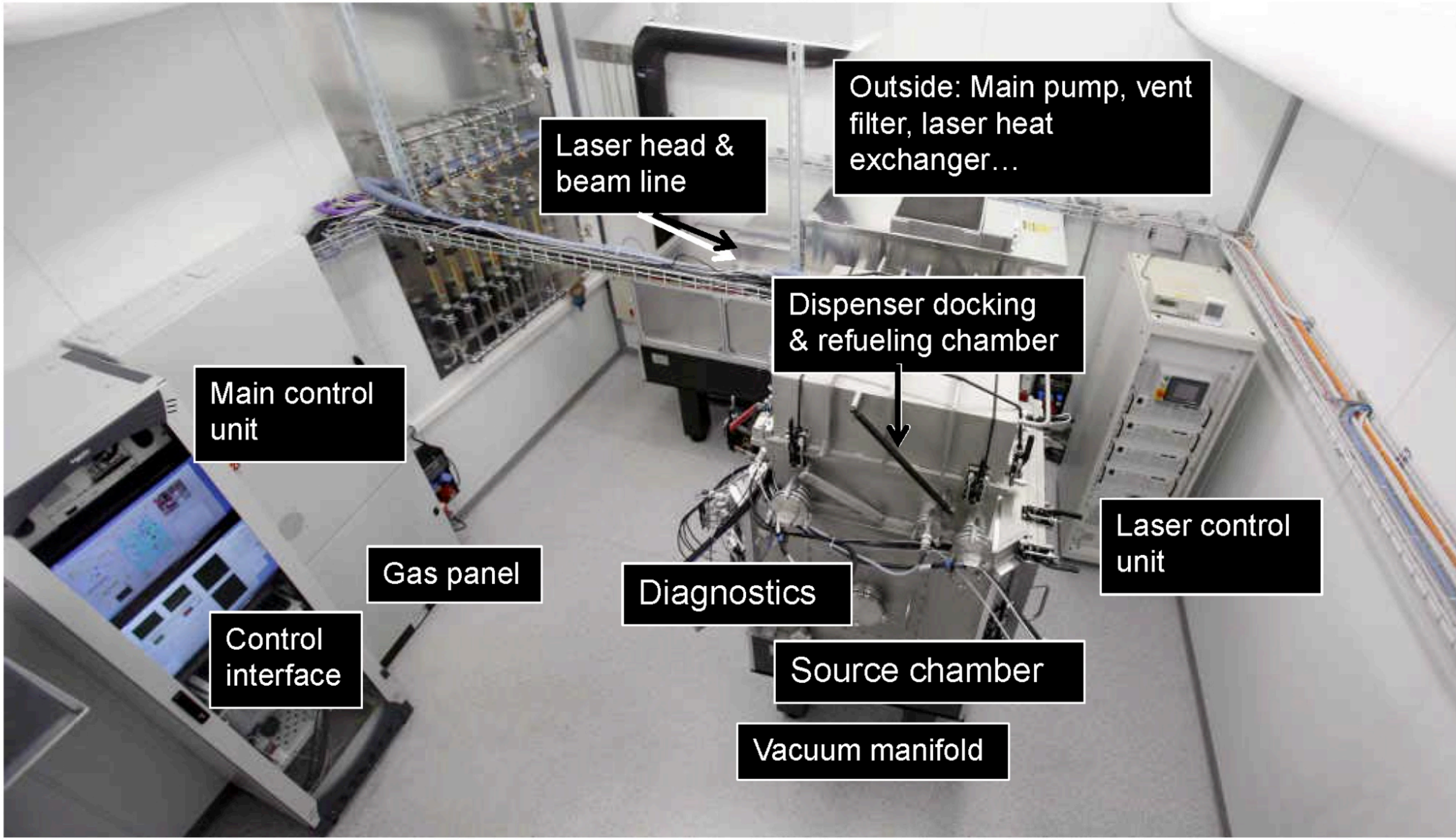
Optimizations of droplet generator technology

ALPS II Facility

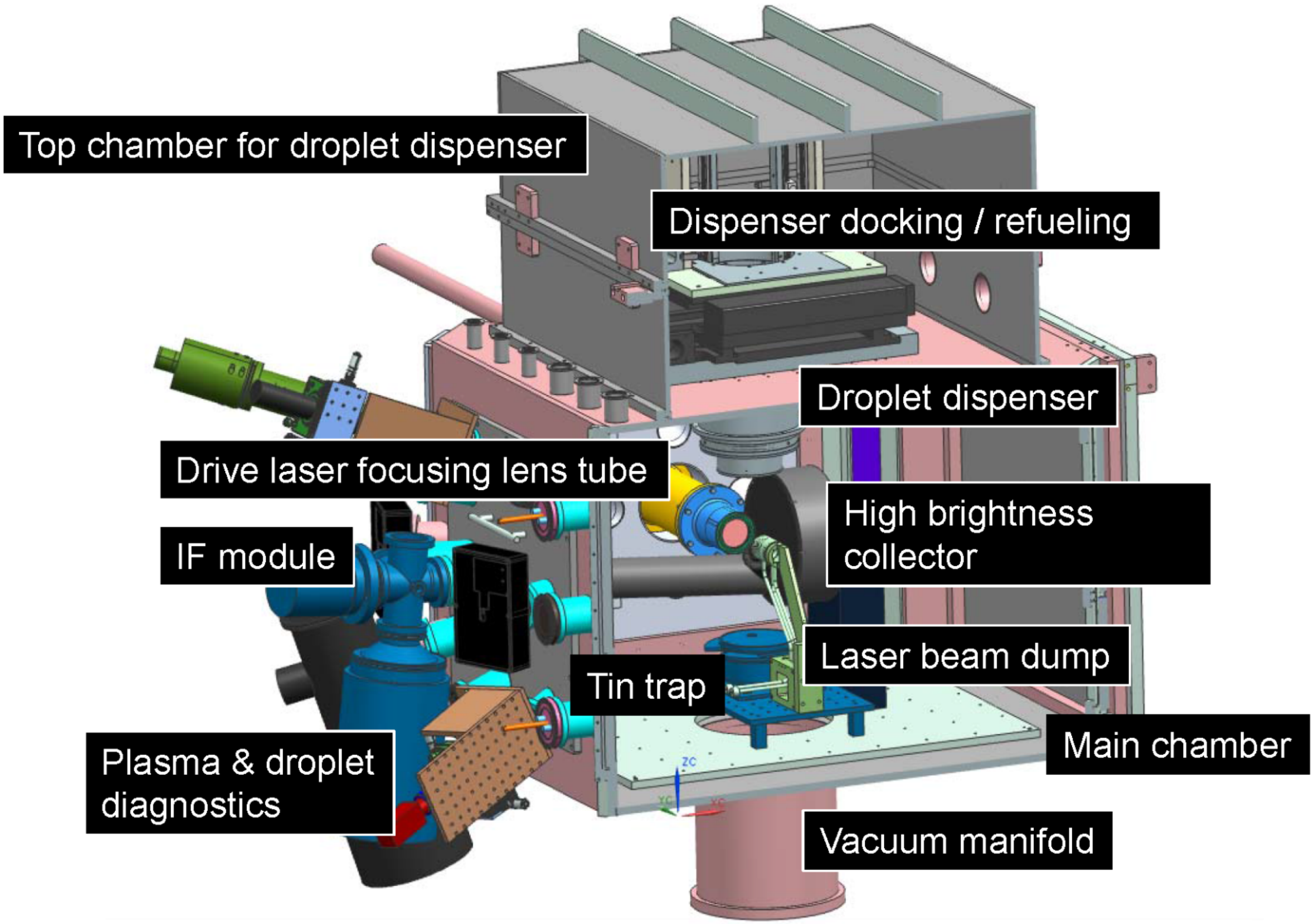
- Recently built lab accomodates the ALPS II facility
- Lab operational since February 2013 and fully operational since September 2013

- Equipped with a Nd:YAG laser (average power of 1.6 kW, emission wavelength of 1.064 μm, up to 20 kHz repetition rate).
- Large capacity droplet dispenser, mounted on 3D motion stage
- Droplet tracking system, coupled to x-y motion, with integrated laser triggering
- Fully automated operation through single control unit

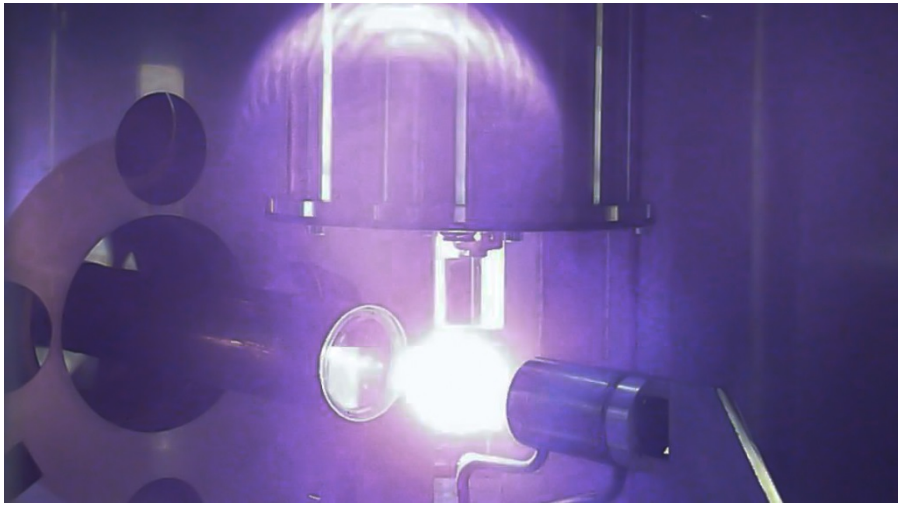
ALPS II Facility Layout



Source Chamber Layout



Source Characteristics



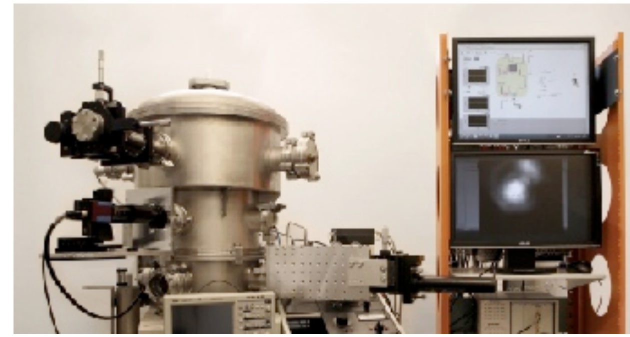
- New high brightness collector for ALPS II
- Inertial debris mitigation optimized for stopping ions / neutrals and minimizing EUV absorption

Parameters	Value
Laser power on target (W)	1300
Laser frequency (kHz)	>6
Laser focal spot size (µm)	70 (FWHM)
EUV source size (µm)	95 (FWHM)
Conversion efficiency (%)	>1%
Source power at the source (W)	>12
Source brightness (W/mm^{2}sr)	>200

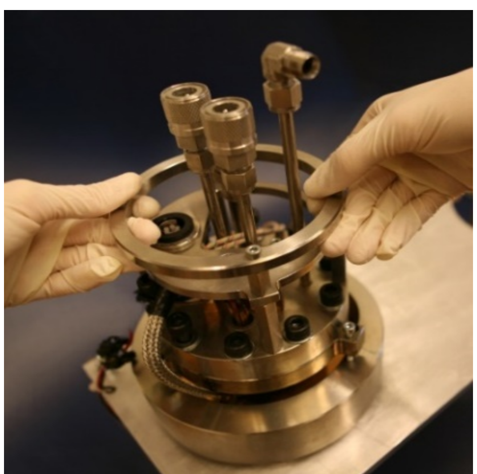
Droplet Generator Technology (DTF)

Droplets: key technology for the LPP sources

- regenerative targets
- reduction of debris through controlled droplet size
- possibility to synchronize the droplet with the laser pulse.

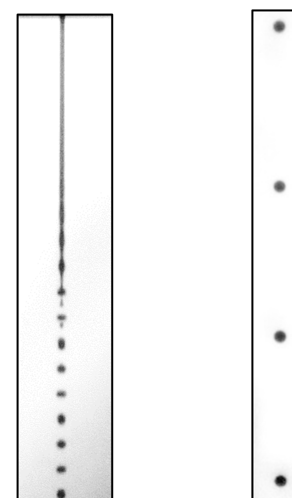


At the LEC, the 5th version of patented in-house dispenser is currently used in ALPS II



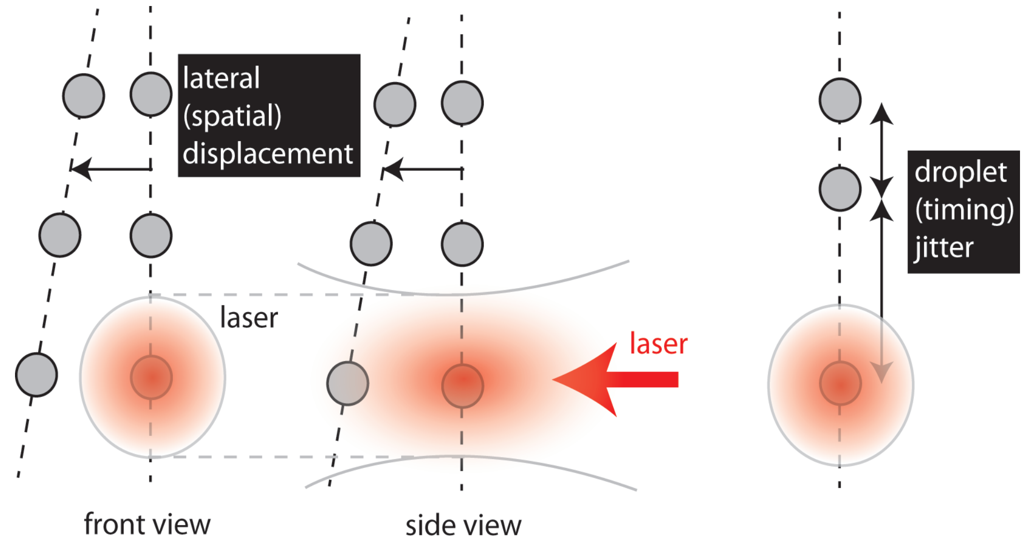
Cartridge run time: up to days
Droplet frequency: up to 100 kHz
Droplet Diameter: down to 30 µm
Droplet Spacing: up to 0.5 mm

Droplet generation through breakup of a tin jet and tin droplet at 8 kHz recorded 220 mm away from the nozzle



Droplet Instabilities:

- Droplet stability directly affects source stability, which is a major issue in today's EUV sources
- Droplet Instabilities in the horizontal plane
- Droplet instabilities along the droplet train

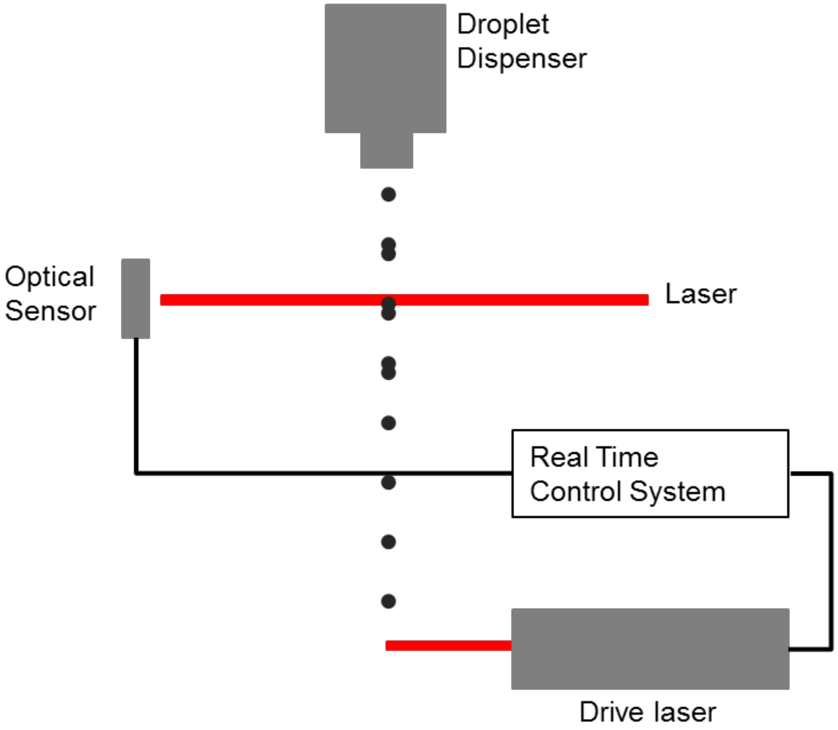


B. Rollinger, Droplet Target for Laser-produced Plasma Light Sources, PhD Thesis, 2012.

Need of a control system able to stabilize the droplet target in space

Closed loop droplet tracking system

- Compensation for low frequency spatial drifts of tin droplet train in the (x,y) plane
- Compensation of temporal droplet jitter at plasma site by laser triggering for individual droplets
- EUV scan function included in the feedback loop (development of a fast integrator chip for EUV pulse signal integration)

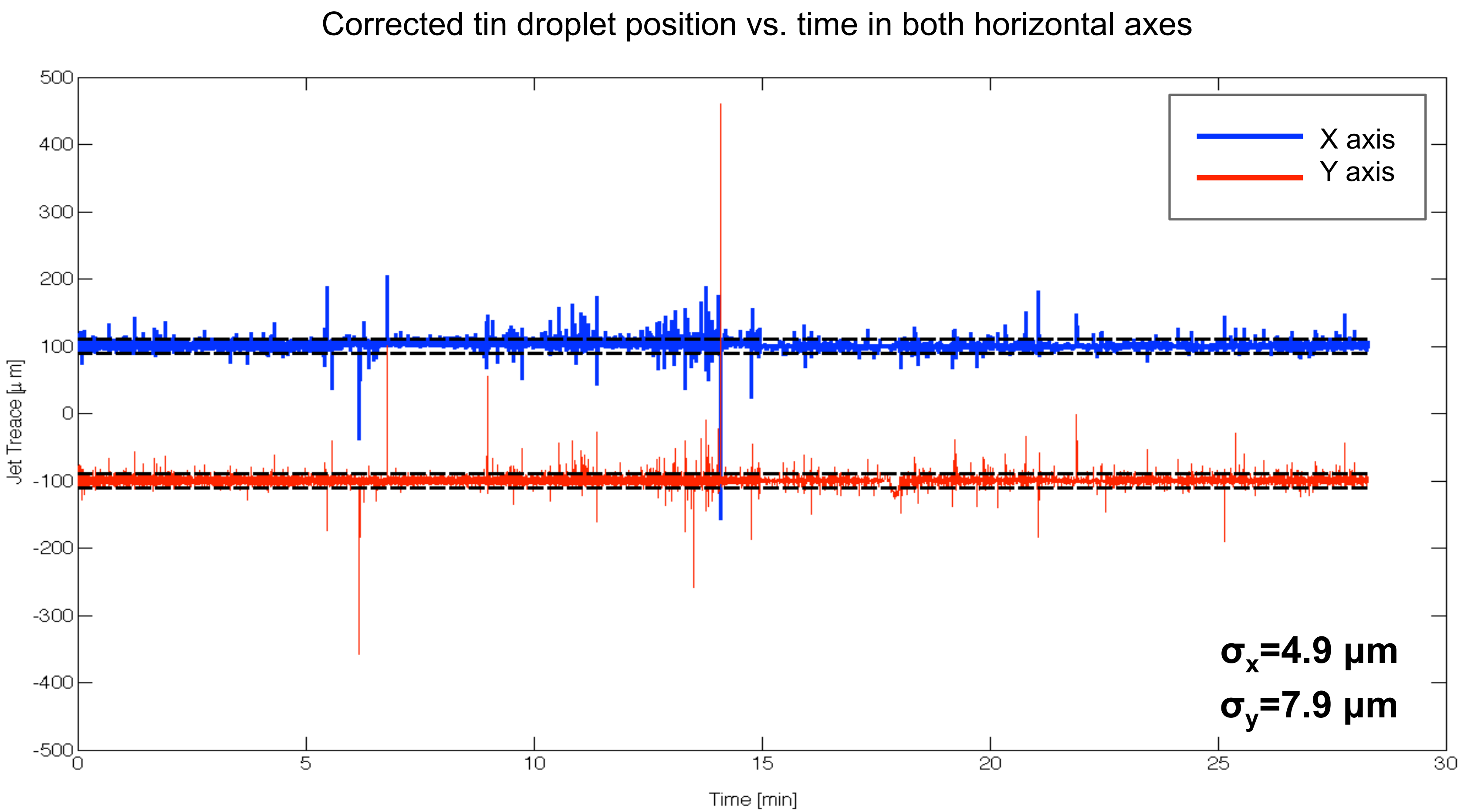


N. Gambino et al., "*Method for controlling an interaction between droplet targets and a laser and apparatus for conducting said method*" , PA, (2012-061)

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Laboratory for Energy Conversion

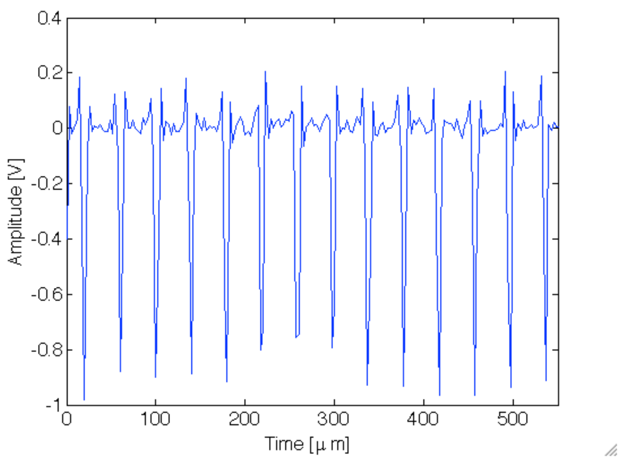
Droplet trace in the (x,y) plane



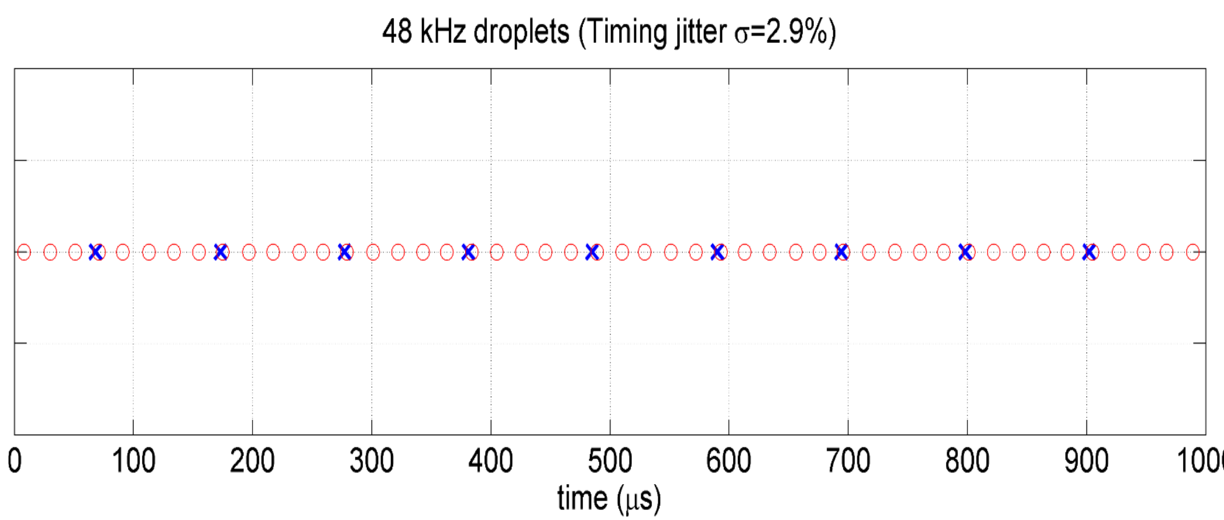
- Spatial resolution: ±5 µm
- Temporal resolution: 0.1 s

Laser Triggering System

- Measurement of individual droplet velocities to consider dispersion in droplet train
- Fast computation of prediction of droplet passage at plasma site



Drop by drop trace at 48 kHz



Example of triggering for 48 kHz (synchronization $\sigma < 20\% \ D_{drop}$)

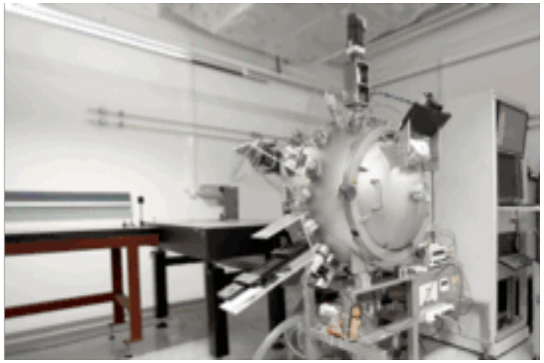
ALPS I: Plasma Science

1. Radiation Detection:

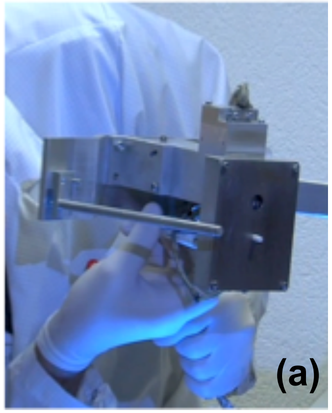
- EUV measured in the +/- 2% bandwidth centered at 13.5 nm with an Energy Monitor (a)
- Robotic arm moves the energy monitor in the whole vacuum chamber, around the droplet target (b)

2. Charged Particles detection for the optimization of the debris mitigation system:

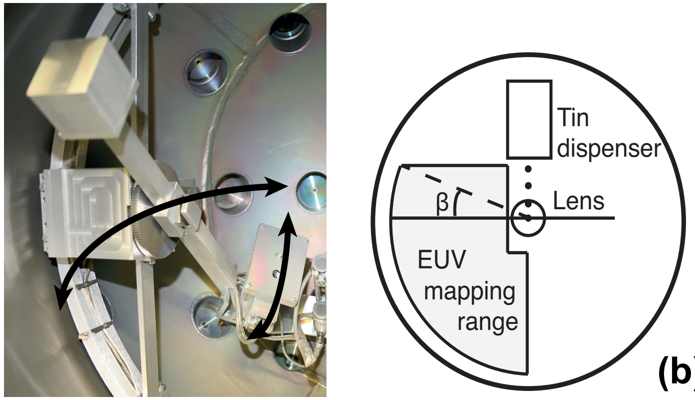
- Faraday Cup's and multiple Langmuir Probe arrays (c)



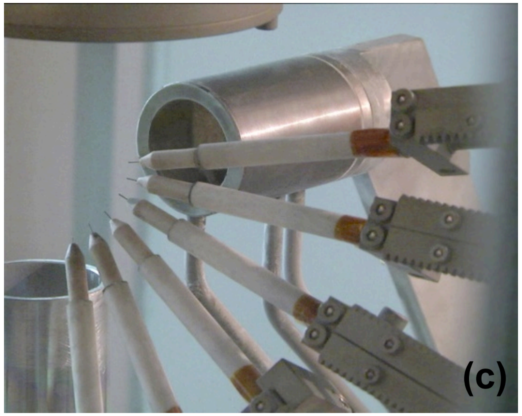
Now operating with a Nd:YAG Laser of 1 J energy, 8 ns pulse duration and FHWM wavelength of 1.064 µm



(a)



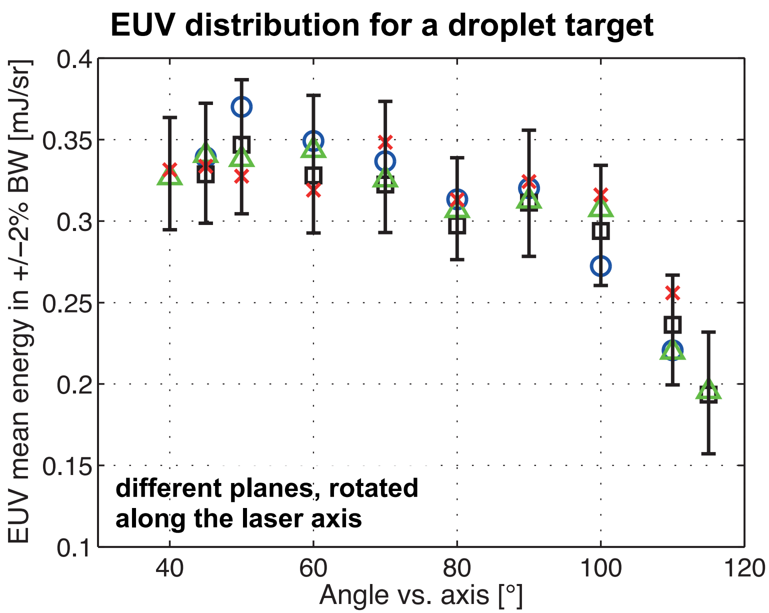
(b)



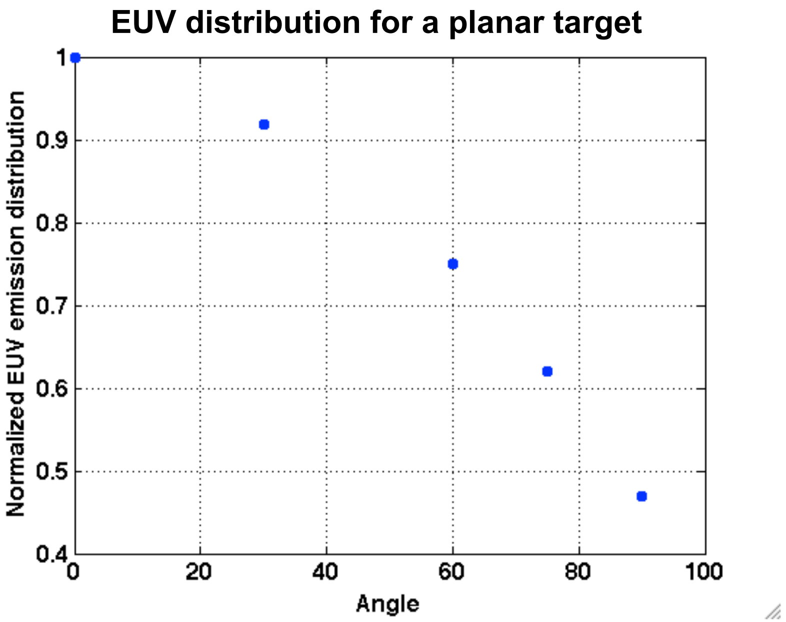
(c)

A. Z. Giovannini et. al, J. Appl. Phys. 114, 033303 (2013)

3D EUV distribution for droplet LPP



A. Z. Giovannini et al., J. Appl. Phys. 114, 033303 (2013)

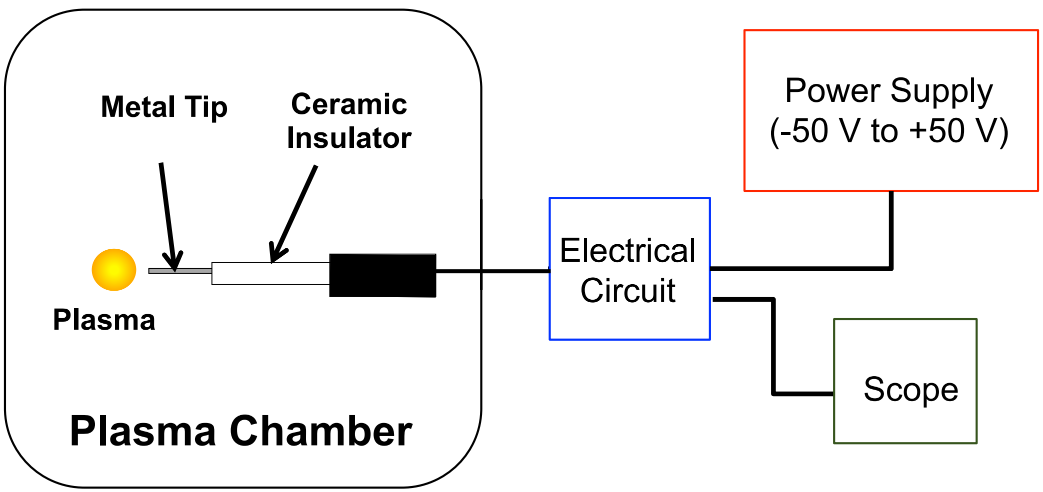


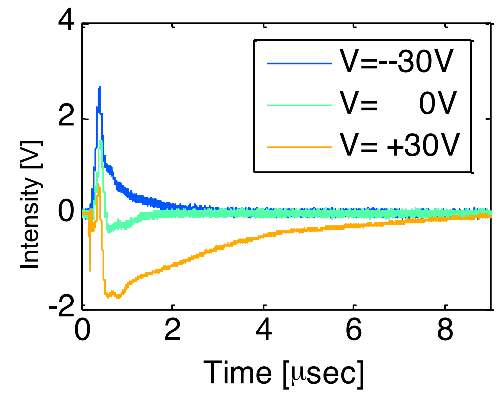
T. Ando et al., Appl. Phys. Lett. 89, 151501 (2006)

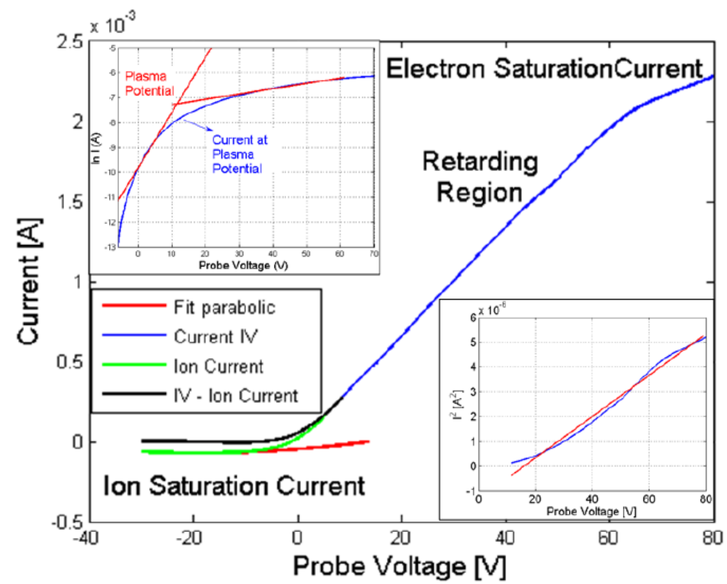
- First 3D mapping of EUV for droplet-based LPP. Important differences when compared to slab targets.
- The EUV distribution from droplet targets remains uniform in the hemisphere towards the laser.
- EUV is emitted also behind (>90°) the irradiated droplet.

more info: poster session November 5, A. Giovannini et. (S37) .

Plasma studies with Langmuir Probes

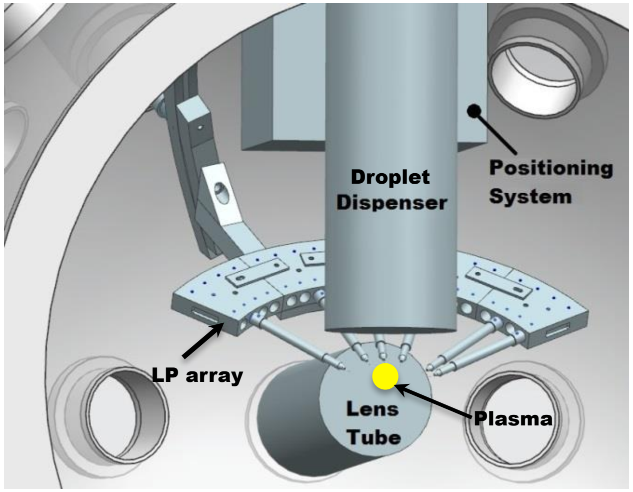






- Electron and ion time of flight (TOF) current signals of plasma are measured.
- Post-processing of the TOF signals and construction of the I-V curves permits to estimate the plasma parameters such as the electron density and temperature.

Multiple array of Langmuir Probes



At LEC a multiple array of Langmuir Probes (up to seven probes) has been designed and constructed:

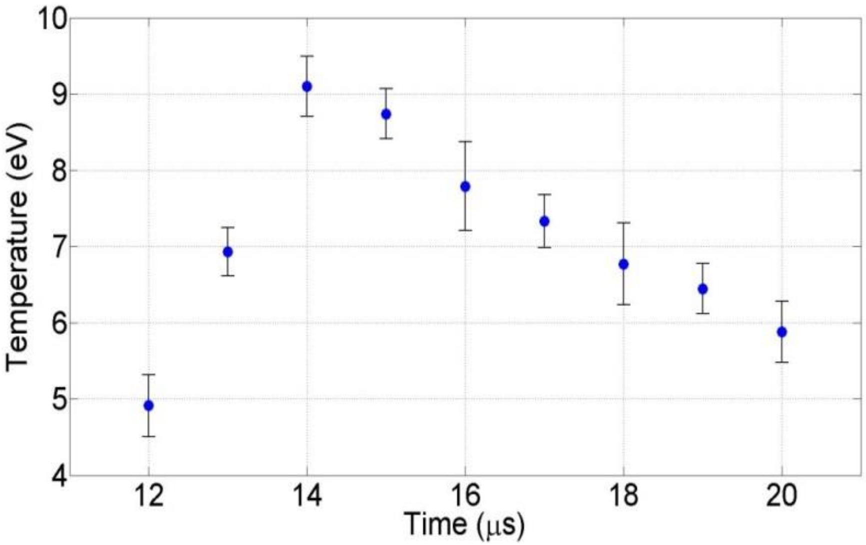
- Up to seven probes were used to measure the plasma parameters in the ALPS I facility
- The LP's were placed at different distances from the droplet target position

Electron temperature versus time obtained for the forward plasma expansion

$$I_i^S = (1+\epsilon)e(v_{drift} + v_{th})\sum_{i=1}^{n} z_i n_i A_p$$

$$v_{drift} = v_c + v_i$$

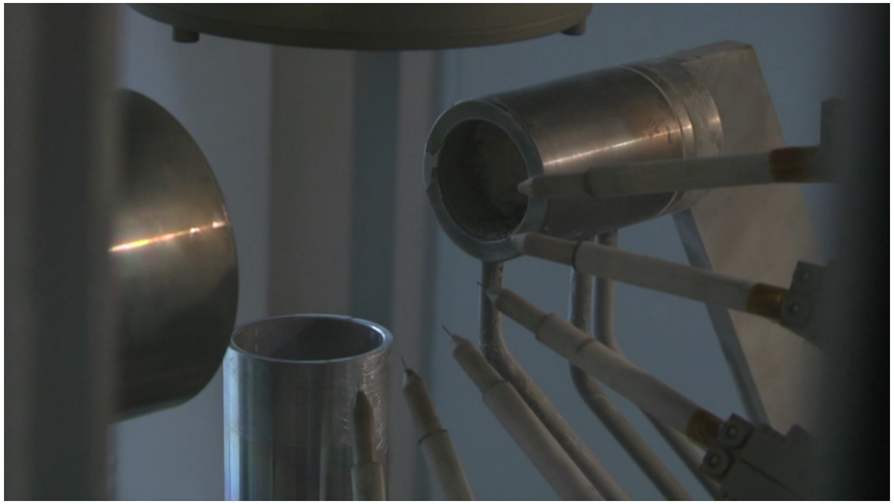
$$I_e^S = \frac{2}{\sqrt{\pi}} n_e e A_p \left(\frac{k_B T_e}{2\pi m_e}\right)^{1/2} \left(\frac{eV}{k_B T_e} + 1\right)^{1/2}$$



S. Lucchini, Fast Charged Particles Detector for the Characterization of a Laser Produced Plasma, Master Thesis, April 2013.

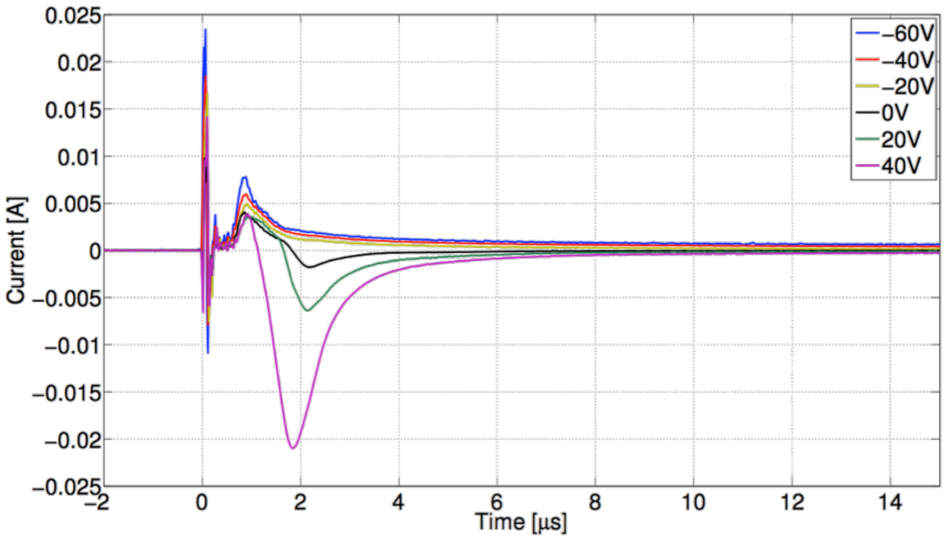
Motorized array of Langmuir Probes

- The probe array is now in a second fully motorized version
- Allows to go very close to the target surface, up to 10 mm from the droplet target
- First measurements were obtained in the ALPS II facility
- 2D mapping and 3D mappings of ion and electron dynamic were obtained



M. Brandstätter, Experimental and Numerical characterization of a Laser Produced Plasma, Master Thesis, November, 2013.

TOF signals obtained at 30 mm from the target



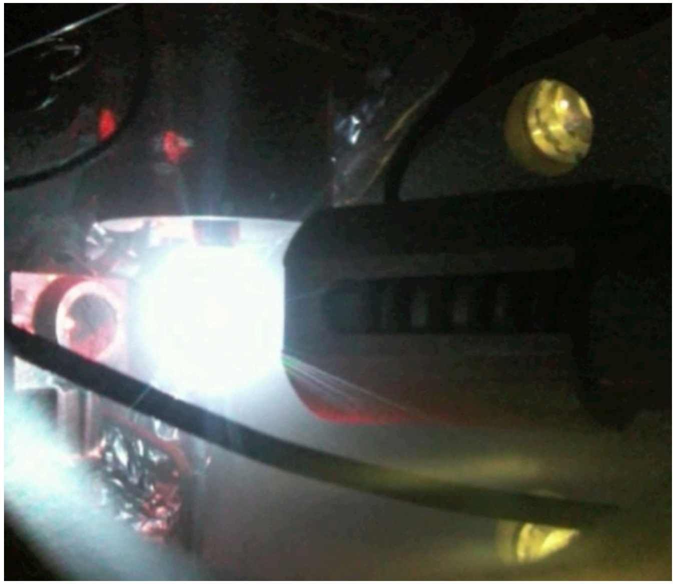
- Analysis of the I-V curves at 10 mm from the target: electron temperatures on the order of 3-5 eV
- accord to numerical simulations obtained with the multi-scale computational tool of LEC

Alternative Fuels for Inspection

- ALPS source operated with indium and gallium droplets.

- Gallium used as droplet target for emission at 6.x nm (Doehring *et al.*, 1994). Current source setup yields ion stages up to Ga X (> 16.7 nm).

- Very high initial droplet stability of both alternative fuels, when compared to tin. Hit rates exceeding 95% for Ga.



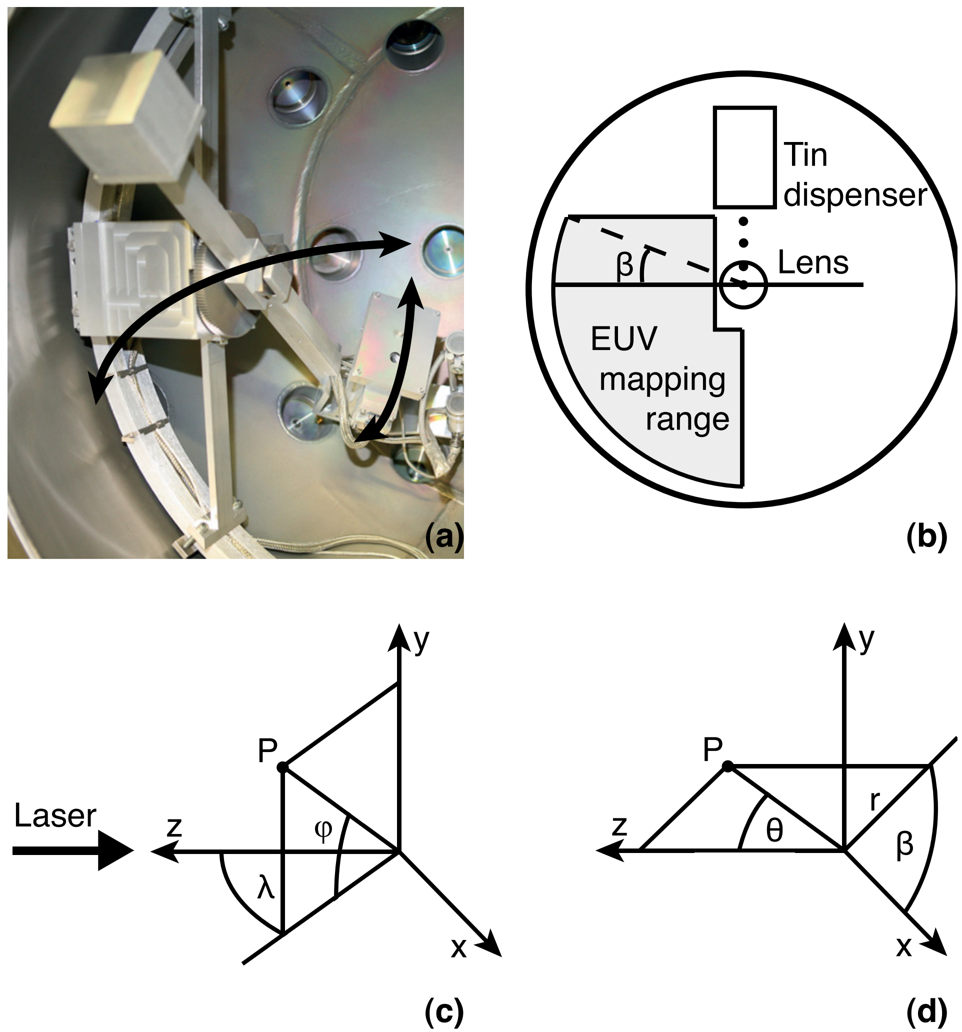
Summary

- The new engineering tool (ALPS II) is fully operational.
- The real time closed loop droplet positioning system was demonstrated. Future tool for droplet diagnostic.
- The drop-by-drop triggering for pulse-to-pulse stability was demonstrated.
- Two additional operating facilities for droplet studies and plasma physics studies (ALPS I) permitted to investigate the droplet plasma proprieties in terms of in band EUV radiation and charged particles emission.
- For the first time, EUV and ion dynamics 3D and 2D mappings were obtained on droplet targets.
- New studies on alternative fuels such as Ga and In.

Thanks for you attention.

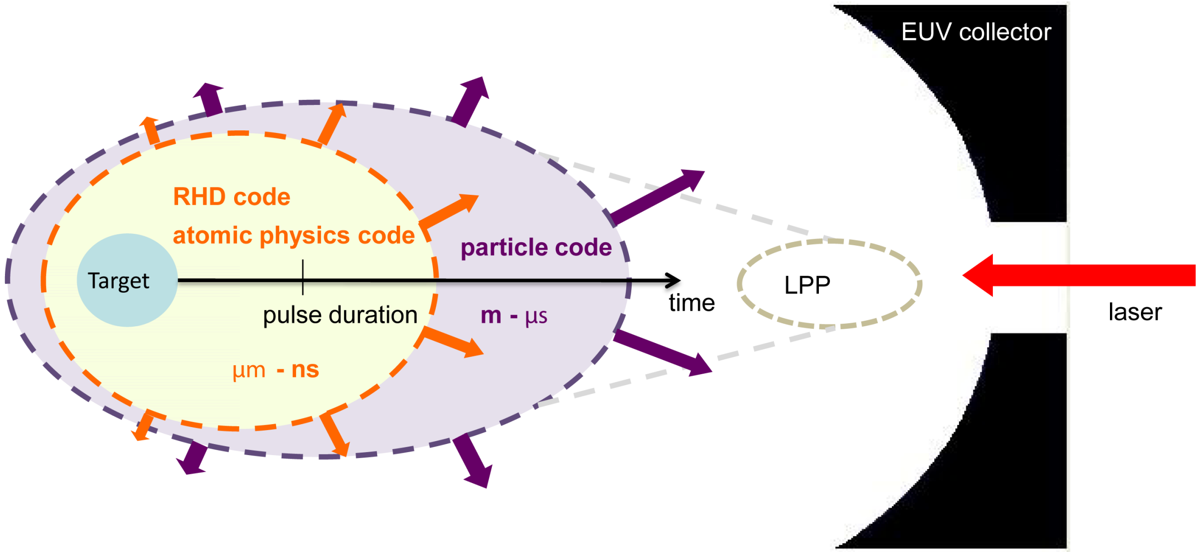
Questions?

EUV Mapping Geometry:



Multi-scale modeling of droplet-based LPP

- Physical processes of plasma formation and expansion extend over a large range (typically 6 orders of magnitude) of time and length scales



- Early stages of laser-target, laser-plasma interaction modeled using a radiation hydrodynamic (RHD) code, together with atomic physics code for radiation modeling.
- The advanced expansion stages (rarefied flow) are modeled using a combined Particle-In-Cell (PIC, electric / magnetic field modeling) and Direct Simulation Monte Carlo (DSMC, collision modeling) methods, coupled in a hybrid approach to the RHD code.